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Mass transport in biological tissues: Comparisons between single- and dual-porosity models in the context of saline-infused Radiofrequency Ablation

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ABSTRACT

Conventional method for modelling mass transport in biological tissues is based on the single-porosity (SP) model, which assumes a homogeneous pressure and concentration in the vasculature. Over the years, the dual-porosity (DP) model, which was originally derived for describing water flow in fractured rocks, has seen an increase in its application to describe flow in biological tissues. In DP models, two porous continua (the interstitium and the vasculature) co-exist within the same space. Flows in both continua are modelled explicitly, which allows for a more accurate representation of the hydraulic interaction between the interstitium and the vasculature. This raises the question on the validity and accuracy of the SP model for describing saline transport in biological tissues. This paper seeks to answer this question by performing a comparative study on the numerical predictions obtained using the SP and DP models in the context of saline-infused radiofrequency ablation (RFA). The results suggest that the SP model has a tendency to underestimate the saline penetration depth inside the tissue. Results from the present study are applicable only in the context of saline-infused radiofrequency ablation. They should not be generalized to other medical and biological applications, as comparison between the SP and DP models for these applications may yield observations that are different from those in the present study.

1. Introduction

Radiofrequency ablation (RFA) is a cancer treatment technique that utilizes heat to destroy cancer cells. It is used predominantly for treating liver cancer. In a typical RFA procedure, a metal probe is inserted into the cancerous tissue inside the liver. Electrical current flows along the probe and into the tissue, where its temperature is raised via Joule heating. The increase in temperature causes denaturation of the tissue proteins and this ultimately leads to cell death. At present, cancer tissue larger than 3–3.5 cm in diameter cannot be treated using conventional RFA due to its relatively small effective treatment zone. Moreover, the treatment breaks down when tissue temperature exceeds 100°C. At this temperature, water

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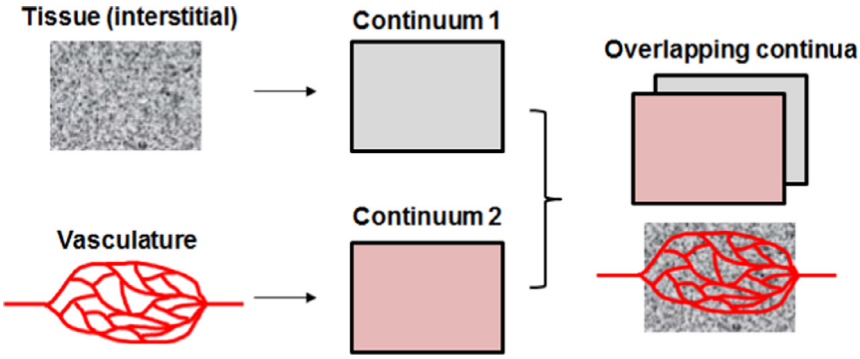

Fig. 1. Sketch illustrating the concept of the dual porosity model.

inside the tissue surrounding the probe begin to vapourise and the low electrical impedance of the water vapour insulates the tissue from the flow of electrical current. Heating eventually stops and smaller lesions are formed as a result [1].

To overcome this, some researchers have suggested to infuse saline into the tissue prior to RFA treatment [2–4]. It is suggested that the abundance of ions in saline can raise the surrounding tissue electrical conductivity, thereby allowing for a greater distribution of electrical current. This leads to greater heat deposition and ultimately the formation of larger lesions. The benefits of saline-infused RFA have been proven in laboratory studies; however, its clinical implementation remains far from realized [3]. This is because the flow of saline, when infused into the tissue, is very difficult to predict. If the infusion rate is too high, there is a risk of extravasation beyond the boundary of the cancer tissue. This can cause some part of the healthy tissue to be ablated, thus leading to undesirable damage. On the other hand, if the infusion rate is too low, the amount of saline that is infused into the tissue may not be sufficient to ablate the cancer tissue. As a result, multiple applications of RFA may be required to complete the treatment procedure.

A proper understanding of how saline behaves inside the tissue can facilitate with the development of saline-infused RFA. In this context, mathematical and computational modelling techniques play a vital role since visualization of the saline in vivo is very difficult and costly. When saline is infused into the liver, it can flow through the interstitial space (interstitium) or get absorbed by the vasculature and lymphatic system. The primary force driving these exchanges is the pressure (mechanical + osmotic) gradient. One of the earliest models to describe the transport of fluid and solutes in biological tissues was developed by Baxter and Jain [5,6]. In their model, the tissue is assumed as a porous medium, where the voids of the interstitium and the cells represent the pores and the matrix, respectively [7]. With the porous medium assumption, fluid transport inside the tissue is described using Darcy's law, while the fluid interactions between the interstitium, the vasculature and the lymphatics are described using the Kedem–Katchalsky theory [8]. To describe the transport of solute within the tissue, Baxter and Jain [5,6] employed the convection–diffusion equation, where the solute exchange between the interstitium, the vasculature and the lymphatics are addressed through properly formulated sources and sinks.

Although not defined as such by the authors themselves, the model of Baxter and Jain [5,6] may be regarded as a single-porosity (SP) model for transport in biological tissues due to only the interstitium being considered as the porous domain of interest. One of the underlying assumptions of the SP model is that the pressure and the concentration inside the vasculature is constant and homogeneous throughout the entire tissue. This assumption is not entirely accurate, as the vascular pressure upstream is likely to be different from those downstream. Nevertheless, the SP model has been employed by many researchers to investigate various problems pertaining to fluid flow in biological tissues. For example, Pusenjak and Miklavcic [9] and Soltani and Chen [10] employed the SP model to investigate the interstitial pressure in solid tumours. Others, such as Linninger et al. [11] and Allard et al. [12], developed SP models of the brain to investigate the efficacy of convection-enhanced drug delivery. Barauskas et al. [13] explored the possibility of using saline infusion as a means for enhancing radiofrequency ablation treatment of liver cancer.

The dual-porosity (DP) model was originally developed for the civil engineering discipline to describe water transport in fractured rocks [14,15], but has since been applied to the study of fluid transport in biological tissues due to the similarity between fractured rocks and biological tissues. Unlike the SP model, the DP model assumes the vasculature as a porous continuum that co-exists with the porous interstitium. Within the vascular continuum, the blood capillaries represent the voids of the porous continuum, while the matrix is represented by the non-existent surrounding space. This is illustrated in Fig. 1. Fluid transport in both the interstitium and the vasculature are modelled using Darcy's law, while the hydraulic interaction between the two continua is described based on the Kedem–Katchalsky theory. Similar expressions for the convection-diffusion equation can also be derived for the DP model [16]. Rohan and co-workers [17,18] employed DP models to solve tissue perfusion problems through multiscale modelling and homogenization techniques. Erbertseder et al. [16] coupled the DP model with the Vascular Graph Model [19] to investigate cancer-therapeutic transport in the lung. Bonfiglio et al. [20] and Siggers et al. [21] employed DP models to describe microcirculation inside the liver lobule. In this case, the vasculature is represented by the sinusoids, while the interstitium is represented by the surrounding liver cells.

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